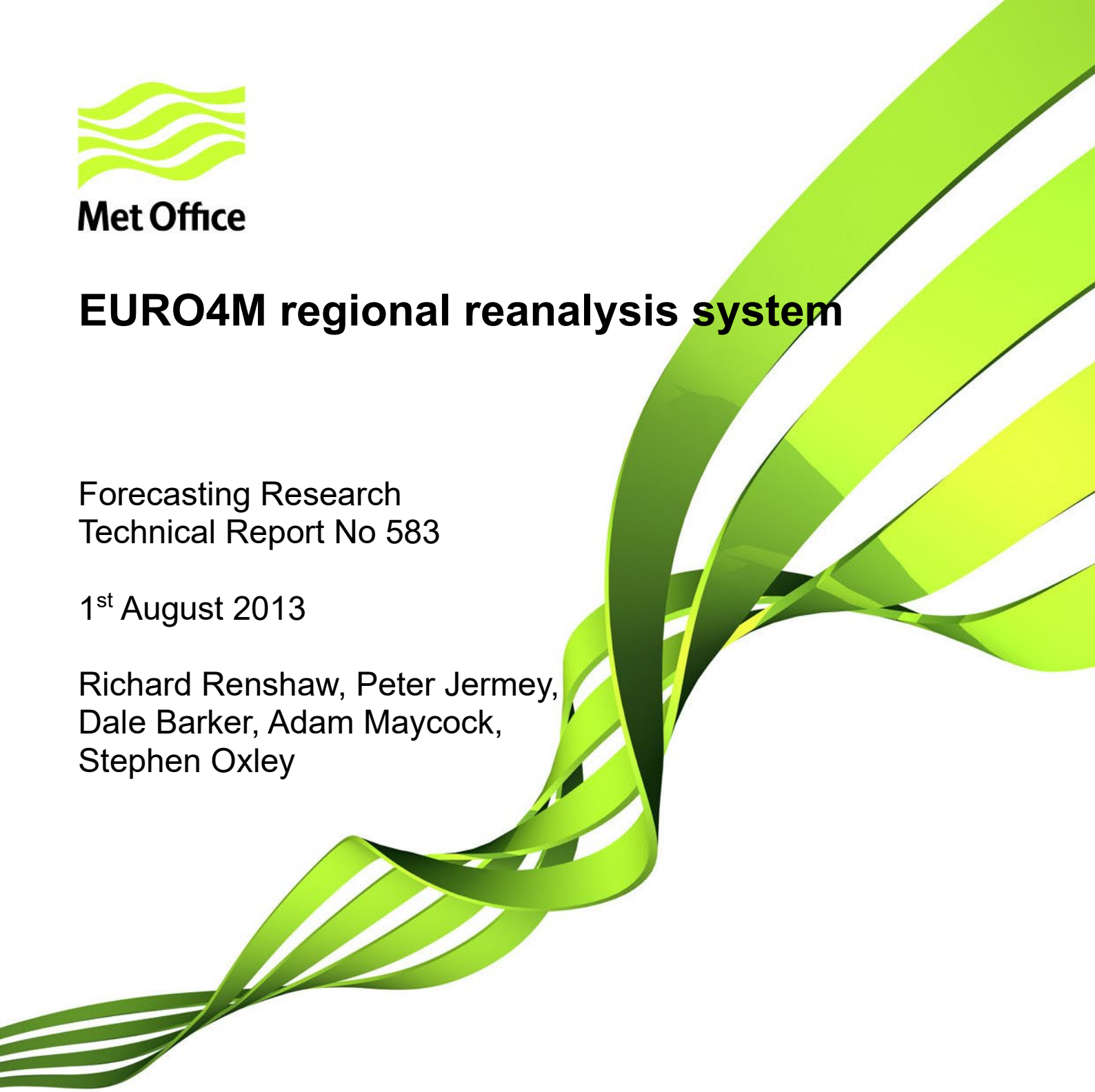

EURO4M regional reanalysis system

Forecasting Research
Technical Report No 583

1st August 2013

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http://www.euro4m.eu/

Abstract

The Met Office has developed a state-of-the-art regional reanalysis system. It is based on systems the Met Office uses for operational NWP (Numerical Weather Prediction). Those systems have been adapted to use historical observations and boundary conditions taken from ECMWF reanalysis archives. A suite of validation tools has been added for validating the reanalysis. The adapted system and validation tools are described here. The system has been run for a two year period (2008/9). Initial results are presented, assessing this reanalysis against other reanalyses and against observations.

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1. Reanalysis system: Science
2. Reanalysis system: Technical
3. Science options
4. Running the reanalysis
5. Validation
6. Early results
7. Future work

1. Reanalysis system: Science

The system is based on the Met Office NAE (North Atlantic/European) regional model (Bush et al, 2006), using the configuration operational in 2013.

1.1 Forecast model

The Unified Model (UM) (Davies et al, 2005) is a gridpoint model using non-hydrostatic dynamics with semi-Lagrangian advection and semi-implicit time stepping. It incorporates a number of sub-grid scale processes, including convection, boundary layer turbulence, radiation, cloud, microphysics and orographic drag. The model domain is a 12km latitude/longitude grid oriented with respect to a rotated pole. The NAE domain was extended further East and South for EURO4M so as to include Turkey and northernmost Africa. A plot of the model smoothed orography (Figure 1) shows the region covered. There are 480x384 gridpoints, with 70 vertical levels extending from near the surface to 80km (Figure 2).

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The UM uses the JULES (Joint UK Land Environment Simulator) land surface model (Blyth et al, 2006) with 4 soil layers.

For the reanalysis, the model was run to produce 24-hour forecasts every 6-hour cycle. This gives extra data by which to assess the quality of the reanalysis.

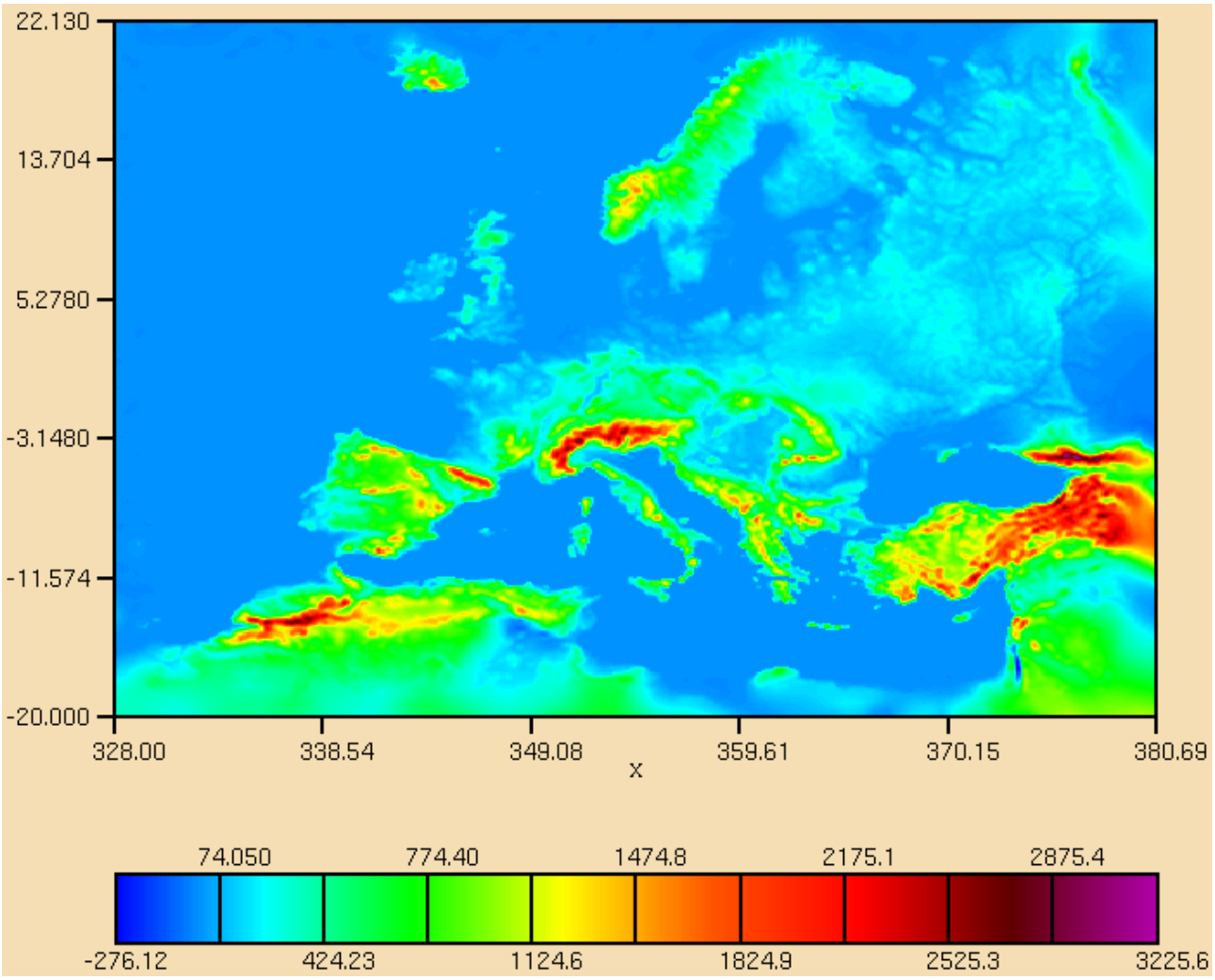

Figure 1: Model orographic height (metres)

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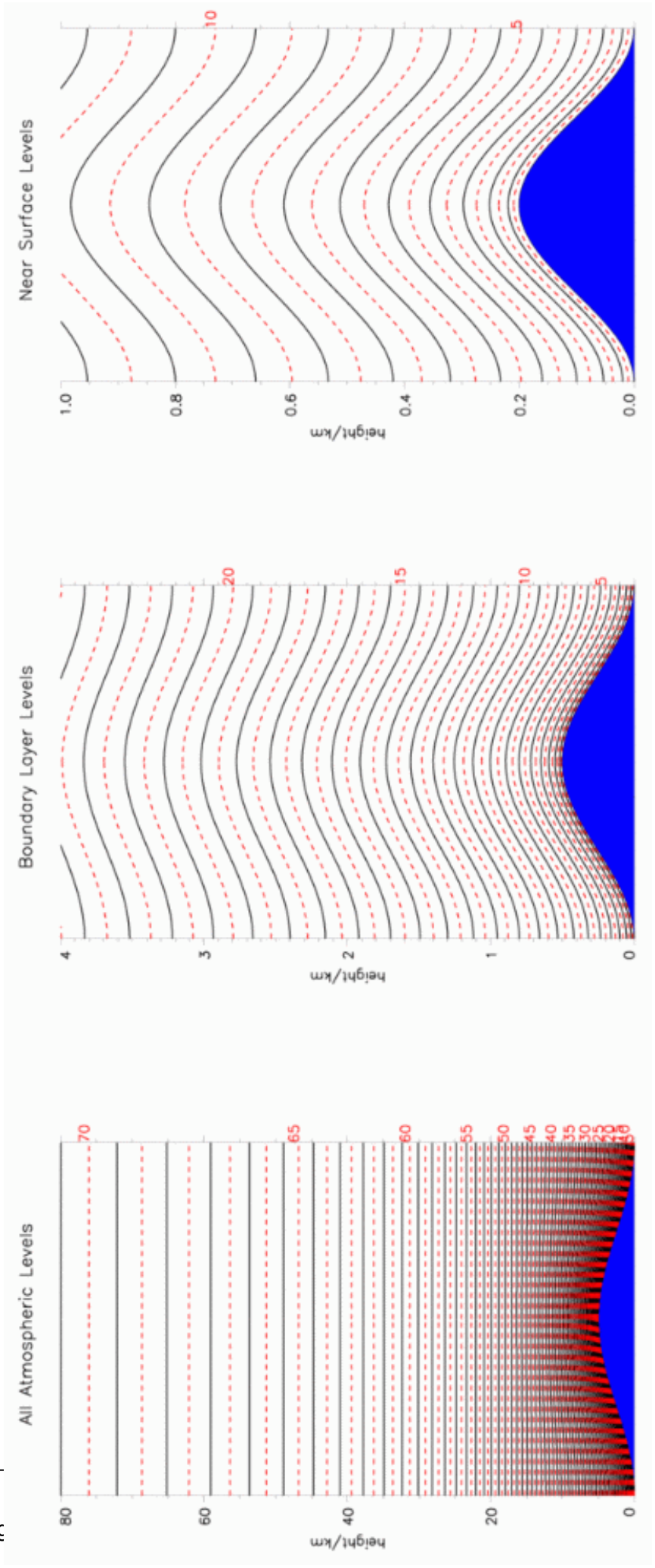

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Figure 2: UM vertical levels, terrain-following near the surface

1.2 Data Assimilation

The assimilation system is 4DVAR (Rawlins et al, 2007). It runs on a 6-hour cycle with analyses at synoptic hours: 00Z, 06Z, 12Z, 18Z. Each analysis (T+0) uses observations from the 6-hour interval T-3 to T+3. The analysis increments are calculated on a 24km grid, half the resolution of the full UM.

The perturbation forecast model within 4DVAR has simplified linearised physics, including a simple boundary layer, cloud latent heat release, convection and large-scale precipitation. 4DVAR applies a weak constraint digital filter to the perturbation forecast (Gauthier and Thépaut, 2001), penalising high frequencies using a pressure-based energy norm ("Jc").

For regional models, a constraint of zero analysis increments is specified at the model boundaries. This allows a double sine transform to be used for the horizontal filtering of the control variables, but requires a good quality driving model to define the large-scale flow, in this case ERA-Interim (Dee et al, 2011).

4DVAR requires background error covariances to be specified (Ingleby, 2001). These are calculated using forecast differences as a proxy for forecast error. In this case the reanalysis system was run for two months, July 2010 and December 2010, producing 6-hour and 12-hour forecasts. The differences between 6-hour and 12-hour forecasts valid for the same time provided the statistics for the error covariances.

1.3 Observations

The following observation types are assimilated:

- Surface (land SYNOPs and METARs, ships, buoys):
  screen temperature, humidity, 10m wind, surface pressure, visibility, cloud
- Upper air (radiosondes, drop sondes, pilot balloons, wind profilers):
  temperature, humidity, wind
- Aircraft (AIREPS, AMDAR):
  temperature, wind
- Satellite AMVs (Atmospheric Motion Vectors):
  wind
- AIRS, ATOVS, IASI:
  radiances

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- SEVIRI:
  clear sky radiances
- Scatterometer:
  surface wind
- Ground-based GPS:
  signal delay (affected by column humidity)
- GPS radio occultation:
  bending angle

Bias correction

Satellite radiances are bias-corrected, using airmass-dependent predictors (Harris & Kelly, 2001). The bias corrections were calculated monthly from an initial run of the 2008/9 period with satellite radiances not assimilated.

Observation selection

Several observation types are thinned where they are particularly numerous. This is done for satellite radiances, which are universally high volume, and for aircraft reports where these are densely packed, for instance near airports.

Various tests are used to reject observations suspected to be of poor quality:

- Background check. Observation values significantly different from the model background are rejected. The threshold for rejection is calculated by a Bayesian scheme and is dependent on estimated observation and background errors.
- Buddy check. Observations failing the background check can be used if they are consistent with other observations nearby.
- Rejection lists. Monthly monitoring of observation minus background (O-B) and minus analysis (O-A) statistics reveal observations that are consistently at variance with the model. For the reanalysis we have used the monthly rejection lists produced for the operational Global and NAE models for 2008/9.

Visibility assimilation

A noteworthy feature is the variational assimilation of visibility observations from surface stations (Clark et al., 2008). The UM includes sources and sinks of aerosol concentration. 4DVAR calculates visibility as a function of, chiefly, aerosol concentration and screen level humidity. Assimilating visibility observations gives information on both those variables.

Cloud assimilation

The NAE assimilates cloud fraction at cloud top derived from SEVIRI imagery (Renshaw & Francis 2011). Cloud top temperature is inferred from the radiances, and cloud top height is then assigned based on NAE background temperature profiles. The current system does not have the flexibility to reprocess historical data for a reanalysis, although there is

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work underway that will provide this capability. Instead a scheme has been developed to assimilate cloud base from surface reports. This is described in more detail in Section 3.4

1.4 Starting conditions and lateral boundary conditions

To perform the reanalysis, start fields are required for the start of the run and lateral boundary conditions (LBCs) throughout the period. Both of these are provided by ERA-Interim analyses. These are available 6-hourly at approximately 80km resolution.

1.5 Other model fields

At every 06Z analysis, model fields are updated for:

- Ozone, from monthly climatology
- Soil moisture, taken from operational Global UM. Global soil moisture in 2008/9 was updated using a nudging scheme (Best & Maisey, 2002), based on differences between NWP forecasts and observations of screen level temperature and humidity.
- Sea surface temperature and sea-ice, from the Met Office's Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) (Donlon et al, 2007)
- Snow cover, taken from operational Global UM. This was model-generated until November 2008, when the NESDIS IMS snow product was used instead.

2. Reanalysis system: Technical

ECMWF has assembled a substantial archive of observations for its own global reanalyses. These and the ERA-Interim analyses are archived in MARS (Meteorological Archive and Retrieval System). The reanalysis ran on the ECMWF high-performance computer (HPC), to get direct access to these archives. This required technical work, adapting Met Office systems to read and write from and to MARS, and porting them to the ECMWF HPC.

2.1 Porting and setting up suites at ECMWF

The core Met Office NWP systems (UM, OPS, VAR, VER) were all ported to ECMWF IBM power6 and power7 machines. The Met Office uses a suite control system (SCS) to link these components together into a suite that can cycle over a period. The SCS is an old system that is due to be replaced by a new open source project, Rose (http://www.metoffice.gov.uk/research/collaboration/rose). The Met Office reanalysis suite was an early adopter of Rose.

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Rose builds on the suite scheduling system Cylc (http://cylc.github.com/cylc/) developed by Hilary Oliver at NIWA (National Institute of Water and Atmospheric Research, New Zealand). Cylc can build, run, and monitor suites of any complexity. It has intelligent job scheduling where dependencies are defined for each task, and each task will be released to run as soon as its dependencies are satisfied. Rose adds interfaces, configuration management and further control. Figure 3 shows an example reanalysis suite, with tasks linked by dependencies.

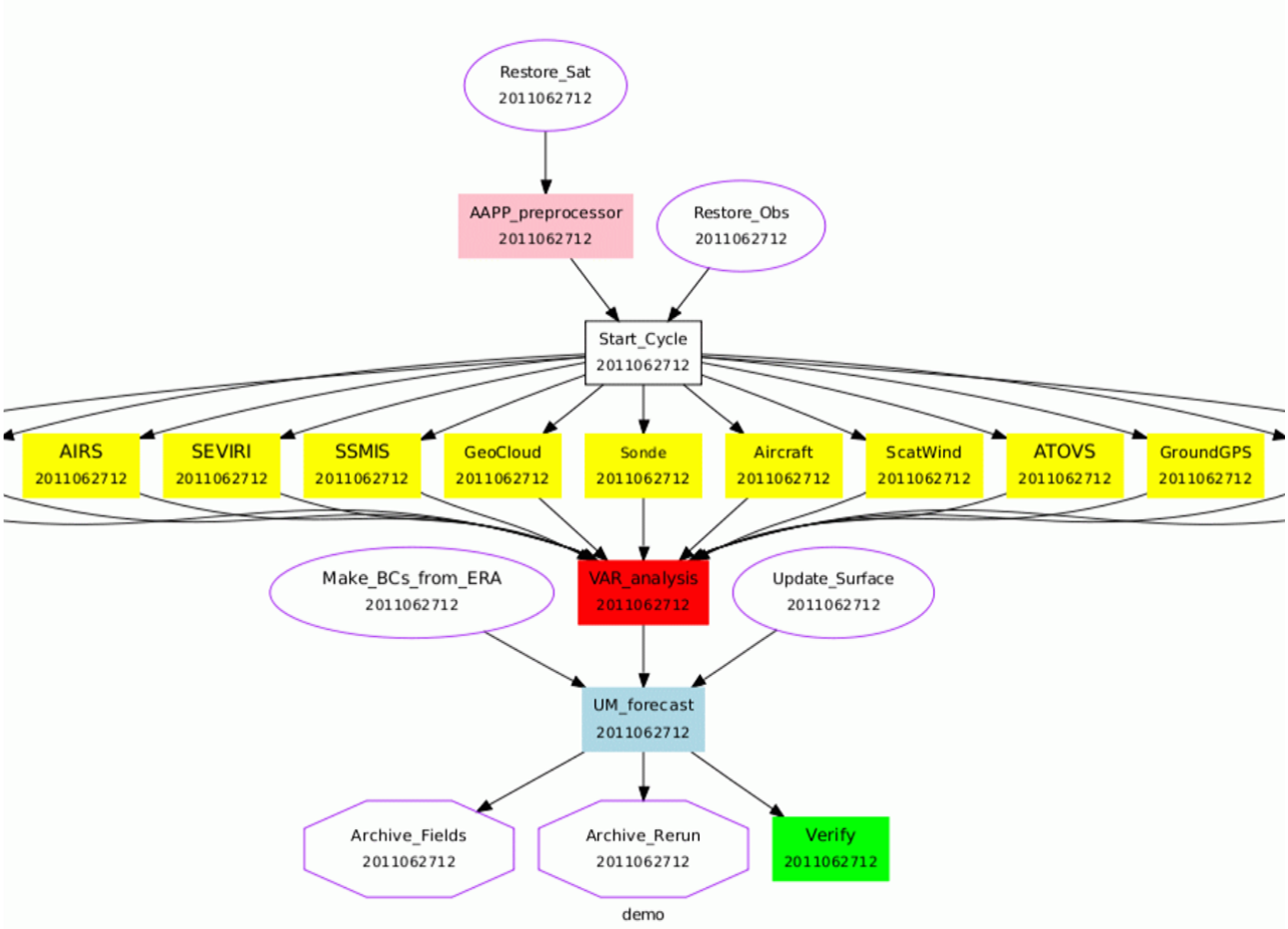

Figure 3: Example rose/cylc reanalysis suite

2.2 Translating file formats

The UM system has its own set of data file formats. Figure 4 shows the main components and data transfers for the reanalysis system. Areas with a purple background use data files in ECMWF BUFR or GRIB formats, and those with a green background use files in UM formats. Any data flow between these two areas requires a translation between data formats.

Code was developed to translate ERA-Interim files (GRIB format) into UM fieldsfile format, and similarly to translate UM reanalysis fields into GRIB format suitable for archiving in MARS.

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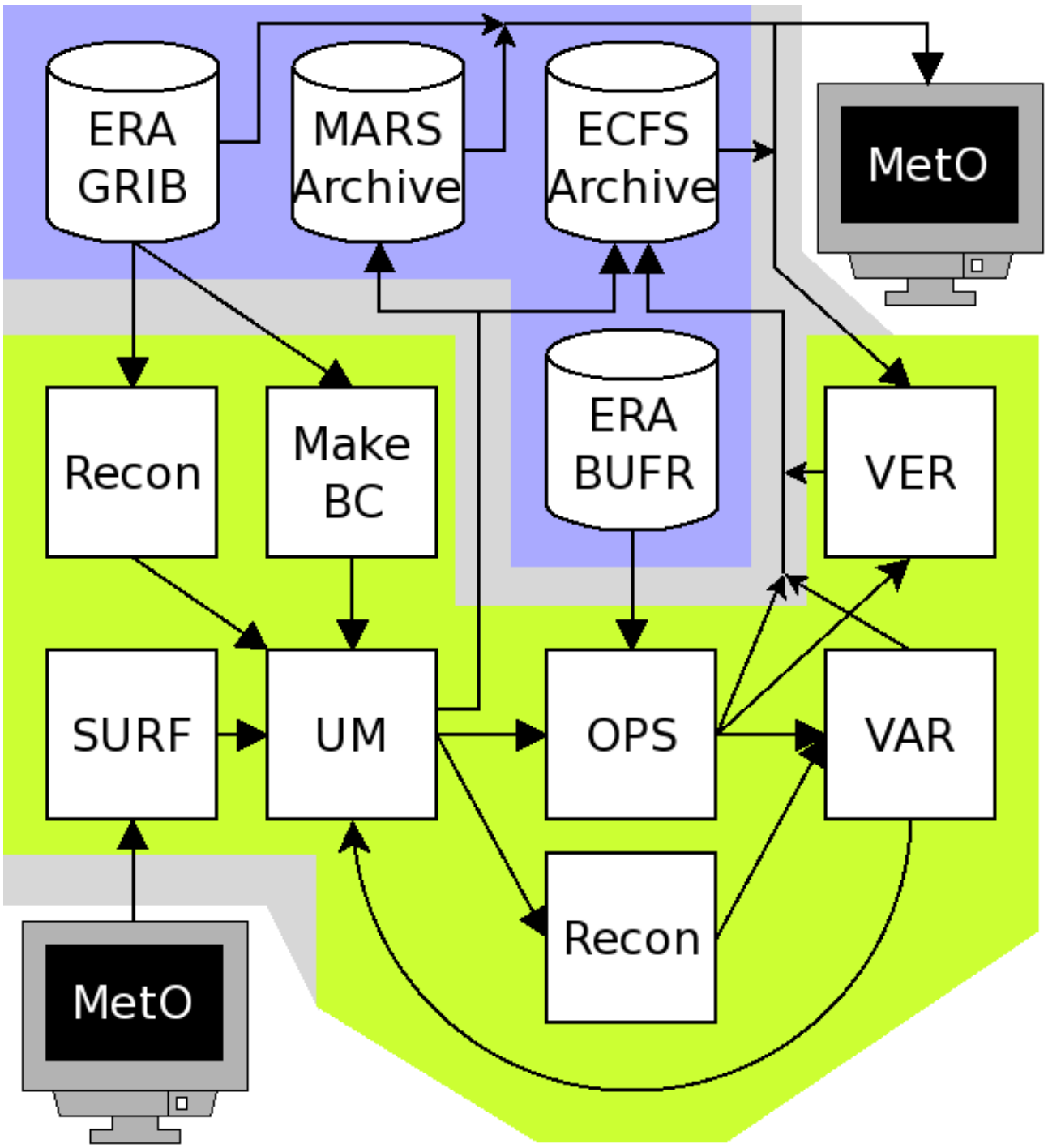

Figure 4: Reanalysis components and data transfers

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2.3 Reading observations

Observations are available from MARS in BUFR format. OPS (Observation Processing System) can read some versions of BUFR, but not the version used at ECMWF. Work was needed to develop in-house BUFR decode software for the ECMWF format. Some observation types required more extensive changes to OPS, for instance satellite winds. AMVs in MARS are not separated by category (ESA, GOES, etc) in the way that OPS required, and radiosonde levels are stored differently. The work required was substantial but has proved beneficial. Comparison of numbers of land surface observations in MARS BUFR and in the Met Office's own archive have revealed gaps in processing of METARS data at ECMWF and of LNDSYN at the Met Office.

OPS is now able to ingest ECMWF BUFR for the following observation types:

- Aircraft
- Upper air
- Surface
- GPS radio occultation

and with the satellite processing described in section 2.4, OPS can also process:

- AIRS
- ATOVS
- IASI
- SEVIRI

OPS is still unable to process ECMWF satellite winds as there are problems interpreting the QC flags. The reanalysis uses Met Office data for:

- Ground-based GPS (not available in MARS)
- Satellite winds (AMVs)
- Scatterometer winds (processed differently at ECMWF)
- Surface cloud reports (interpreted and stored differently in MARS)

2.4 Processing satellite radiances

At the Met Office, satellite radiances are archived as level 1d, where instrument counts have been converted to radiances, and mapped to a common instrument grid (e.g. AMSU and MHS mapped to IASI pixels). At ECMWF, data are archived as level 1b (instrument counts) in BUFR format. Here BUFR data is reformatted to level 1b format. This requires reordering the scanlines from the BUFR messages into time order. The data can then be

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converted and mapped by the AAPP package (http://research.metoffice.gov.uk/research/interproj/nwpsaf/aapp/) to be read by OPS.

2.5 Data archive

Work has been done to convert the reanalysis fields into GRIB format compatible with the ECMWF MARS archive. Fields from the production reanalysis will be archived in MARS. With help from ECMWF, this data will become available to anyone via the web MARS interface.

3. Science options

3.1 3DVAR vs 4DVAR

4DVAR includes a linearised forecast model which allows it to take account of time tendency information in the observations over the 6-hour window. This forecast model makes 4DVAR approximately 30 times as expensive as 3DVAR to run. For NWP, 4DVAR has been shown to have significant positive impact on forecasts (e.g. Rawlins et al, 2007). Here 3DVAR is compared to 4DVAR in the reanalysis for a 1-month period, September 2009.

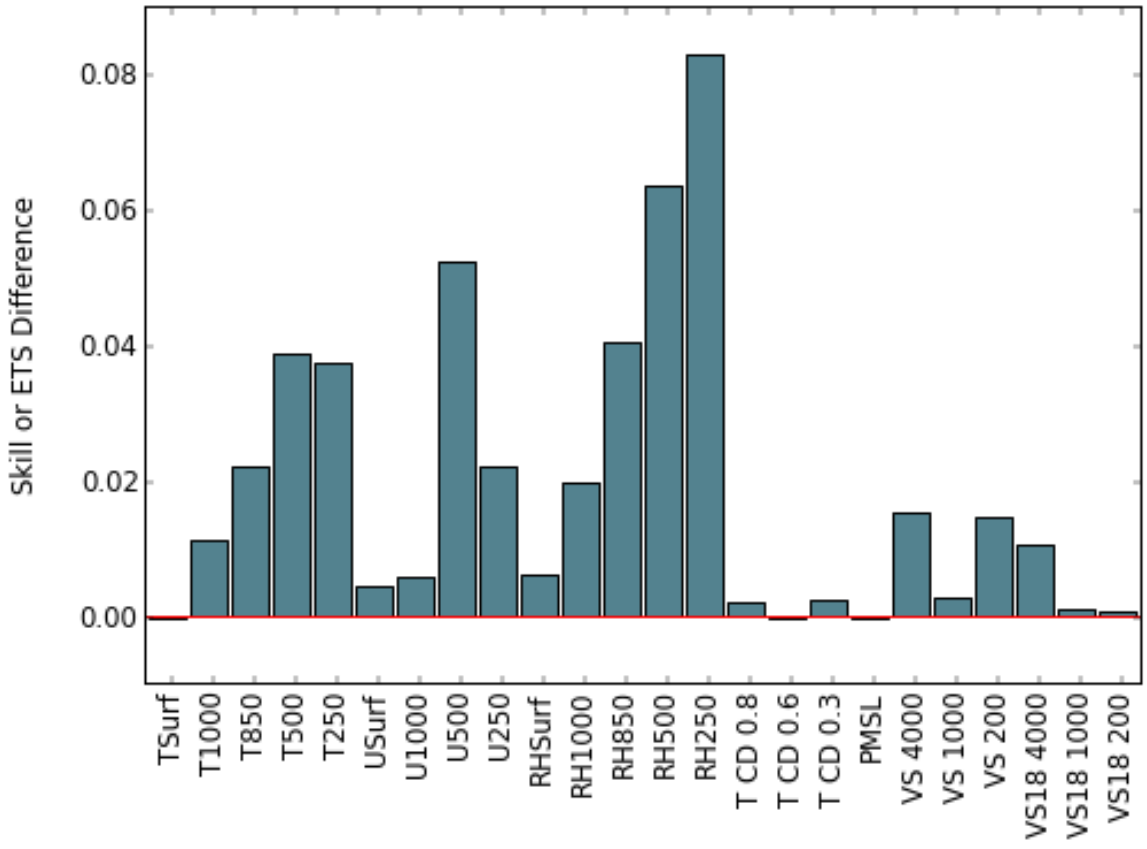

Figure 5: Skill score and ETS differences for 4DVAR vs 3DVAR, Sept 2009

Figure 5 shows improvement in skill score and Equitable Threat Score (ETS) for several

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variables at T+6, verified against surface and upper air observations. Skill score and ETS are defined in Section 5.2. The variables are:

Tsurf	screen-level temperature
T1000/850/500/250	temperature at 1000/850/500/250 hPa
Usurf	vector wind at 10m height
U1000/500/250	vector wind at 1000/500/250 hPa
RHsurf	screen-level relative humidity
RH1000/850/500/250	relative humidity at 1000/850/500/250 hPa
T CD 0.8/0.6/0.3	Total cloud cover, thresholds of 6/4/2 oktas
PMSL	mean sea level pressure
VS 4000/1000/200	screen-level visibility, thresholds of 4000/1000/200 m
VS18 4000/1000/200	T+18 screen-level visibility, thresholds of 4000/1000/200 m

3.2 4DVAR resolution

The expense of 4DVAR can be reduced by running it at lower resolution. For the operational NAE, 4DVAR is run at 36km, one-third the resolution of the 12km forecast model. For the reanalysis, 4DVAR is run at 24km resolution. Figure 6 shows a reduction in RMS error for screen level temperature, demonstrating the benefit of higher resolution. In computer time, 24km 4DVAR is three times the cost of 36km 4DVAR.

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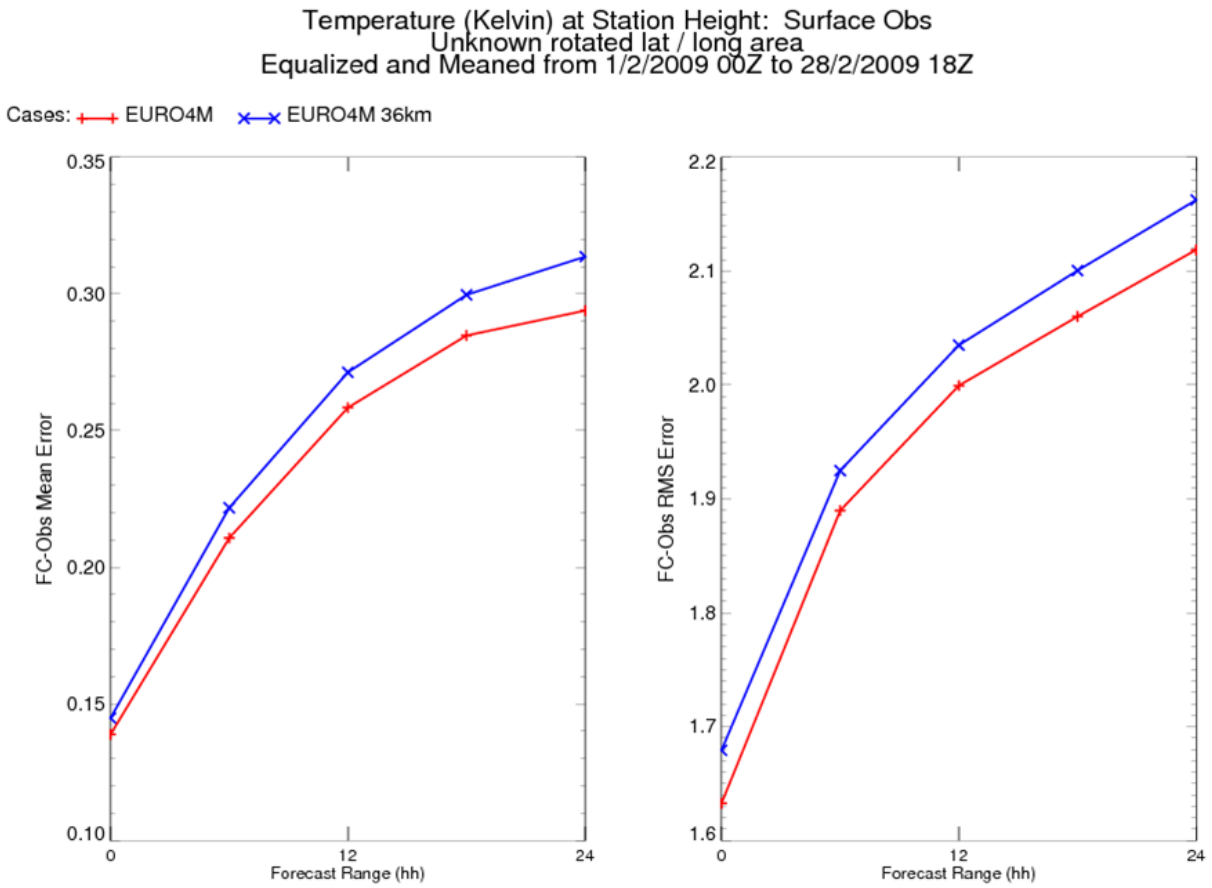

Figure 6: Screen temperature mean and RMS error against forecast range, from 1-month trial of 4DVAR at 24km (red) and 36km (blue)

3.3 Satellite radiance assimilation

Satellite radiances from AIRS, ATOVS, IASI and SEVIRI are assimilated directly in the NAE and also in the reanalysis. To test their impact, a 1-month period (September 2009) was run with and without radiances. Figure 7 shows the impact on T+6 forecasts of using satellite radiances. The impact is overall positive, in particular for temperature, wind and humidity.

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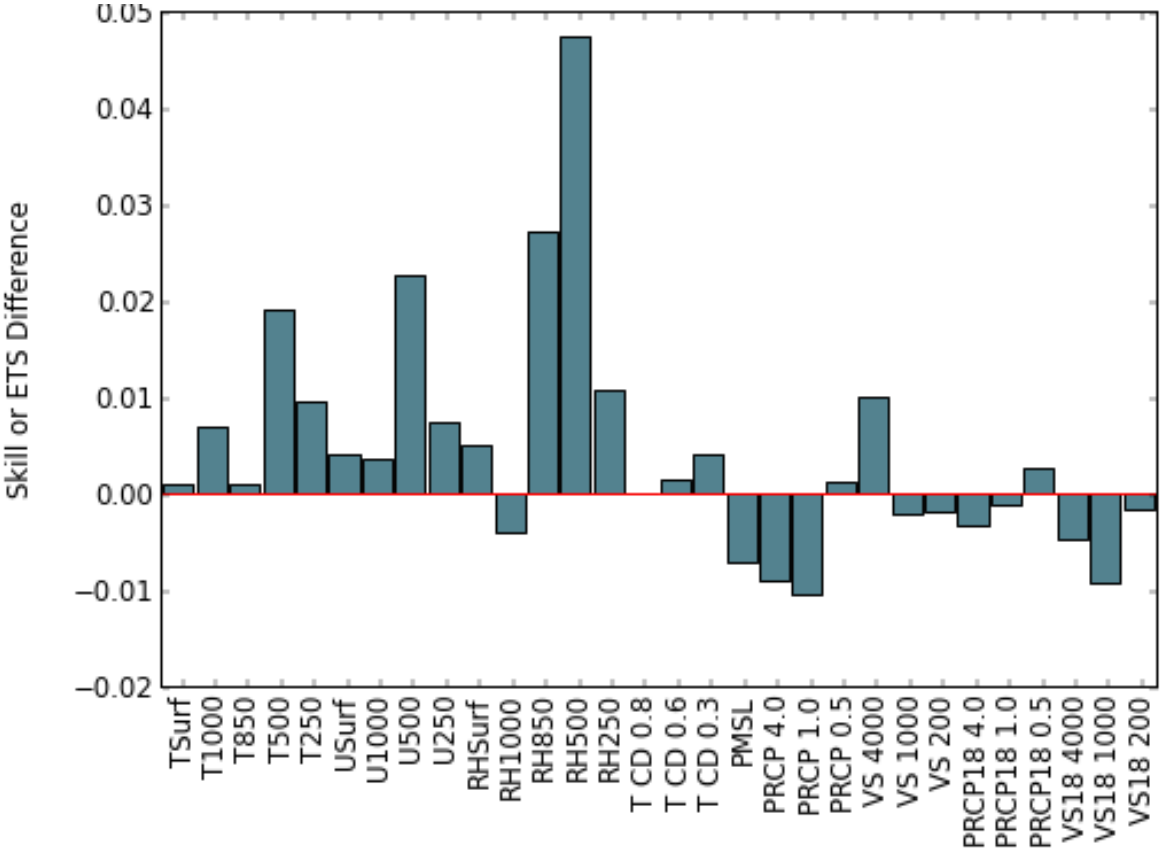

Figure 7: Percentage skill score and ETS differences for Satellites vs No satellites, Sept 2009

3.4 Cloud assimilation

For many years Met Office models for the UK area have assimilated a 3D gridded cloud fraction derived from surface reports and satellite imagery (Renshaw & Francis, 2011). This was a unique Met Office product and not available for the wider European area. Work has been done to assimilate surface reports of cloud cover directly. From the cloud base and other details in the SYNOP report it is often possible to construct a partial vertical profile of cloud cover.

The surface cloud reports were assimilated in the reanalysis. Figure 8 shows the impact of the surface cloud reports at T+6 versus a run without the reports, for September 2009. The impact is mixed. The effect on cloud is close to neutral, and there is a small negative impact on humidity. Trials of cloud assimilation more generally in Met Office operational systems have been similarly mixed, but cloud assimilation has been retained because taken overall it does show a small benefit. For that reason cloud assimilation has been used in this reanalysis.

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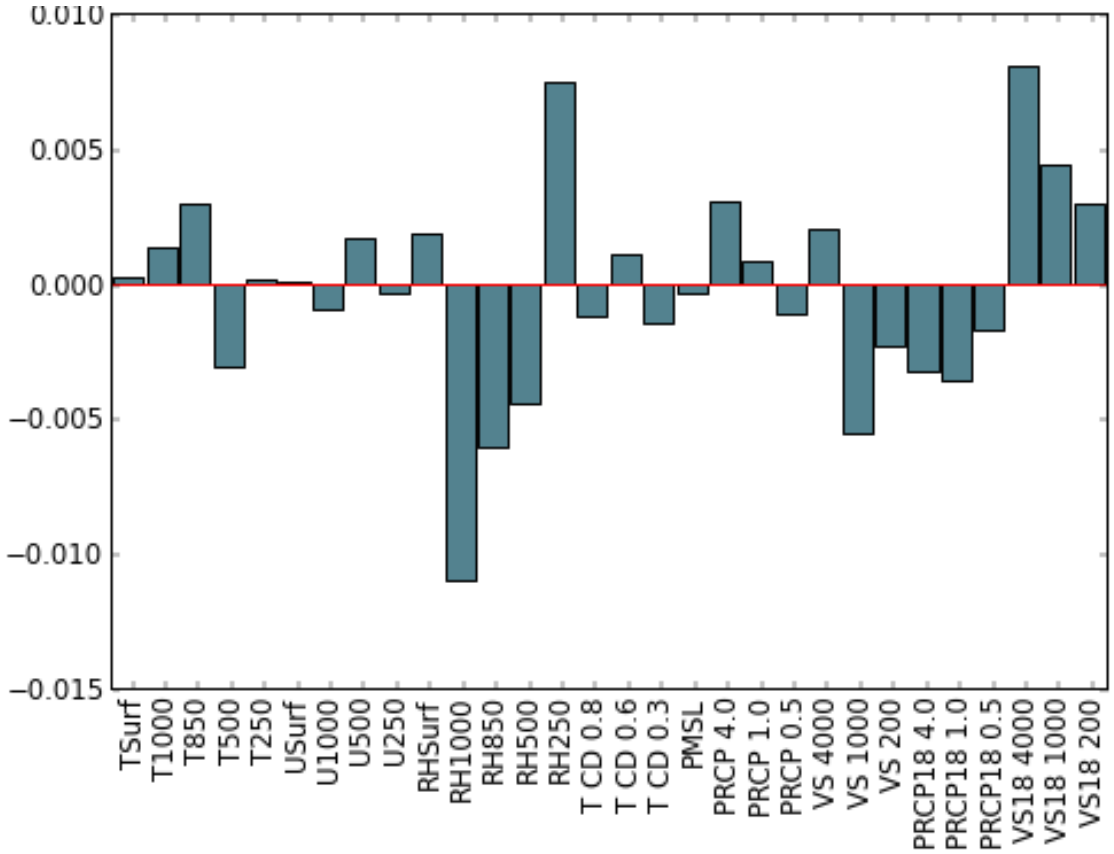

Figure 8: Skill score and ETS differences for Cloud vs No cloud, Sept 2009

3.5 Precipitation spin-down

As well as assimilating cloud, it is hoped eventually to assimilate raingauge accumulations. This is not ready for the production run and so the reanalyses available for evaluation will not include precipitation observations. This is planned to be ready later in the year, to be included in a final reanalysis run which will be evaluated before the end of the project.

The Met Office model, like many other models, has an excess of precipitation at analysis time. This comes about through a temporary imbalance in the moisture fields. The model quickly adjusts and this is not usually a problem. If precipitation were to be assimilated, the initial excess would be a problem. Changes to the initialisation scheme have been developed that reduce that excess. Reduction can be seen in the 10-day average (Figure 9), between the control run (left) and the trial run (right). These changes were included in the reanalysis.

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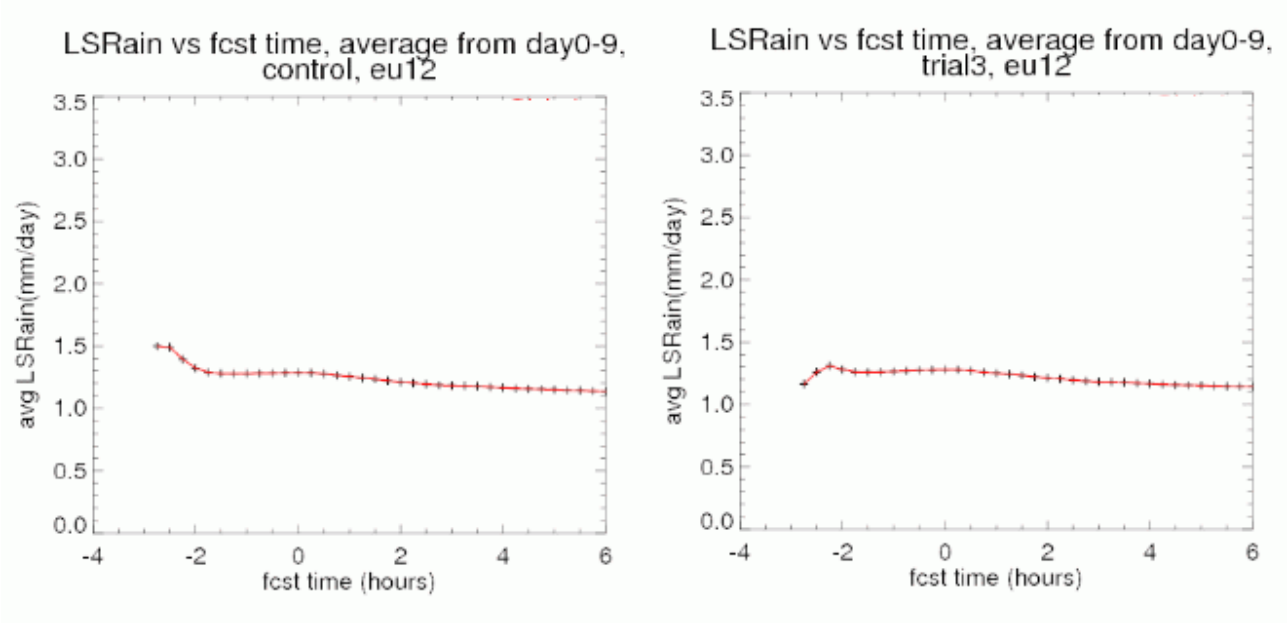

Figure 9: mean model precipitation plotted against forecast range, control (left) and with initialisation changes (right)

4. Running the reanalysis

4.1 Initial Run

The 2008/9 period was run first without satellite data as an initial trial. Upper air data was taken from the Met Office archive, and surface cloud reports were not assimilated. The reanalysis was run as four parallel streams, with 1-month overlap to allow for spin-up from ERA-Interim initial conditions:

A: 01/11/2007 – 30/06/2008
B: 01/06/2008 – 31/01/2009
C: 01/01/2009 – 31/08/2009
D: 01/08/2009 – 31/01/2010

To confirm that one month is long enough for the fields to spin up, analysis fields from runs A and B have been compared over an overlap period (01/06/2008 - 08/07/2008). Figure 10 shows RMS difference in surface pressure. After 7-10 days of spin-up the differences are no higher than later in the run. Figure 11 shows RMS difference in screen-level temperature. Again, there seems to be no trace of spin-up after the first 10 days.

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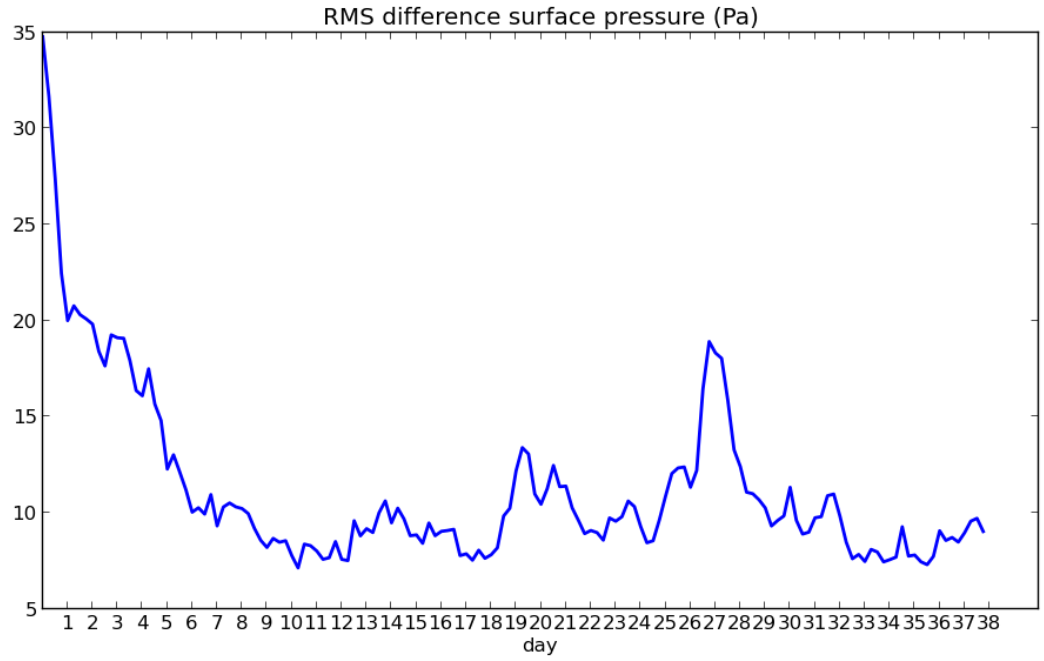

Figure 10 RMS differences in surface pressure over 38 days parallel running, between a spun-up run and a newly started run

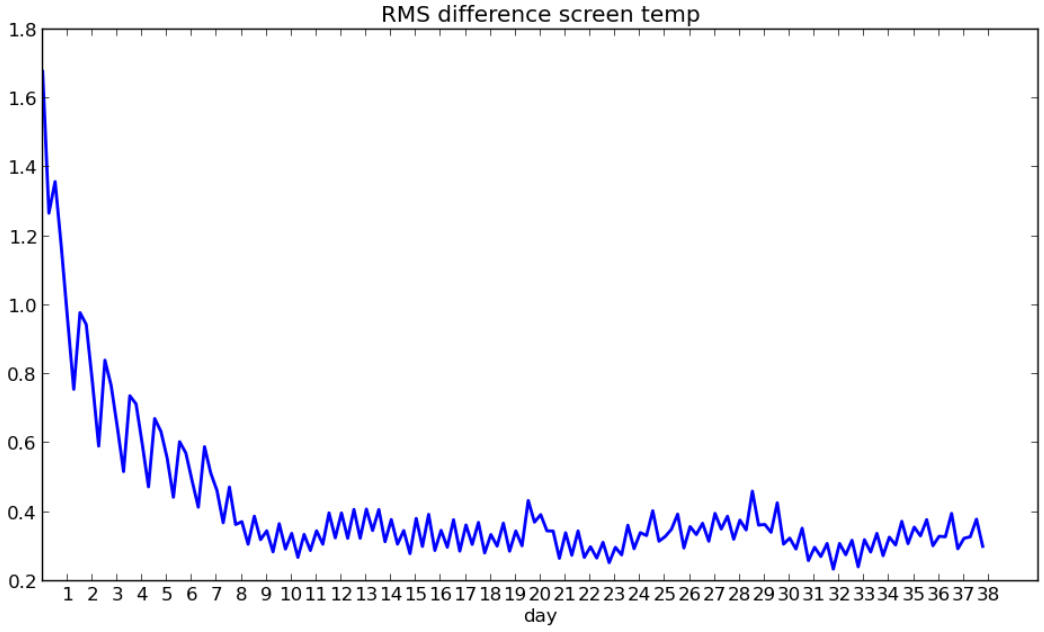

Figure 11 RMS differences in screen temperature (K) over 38 days parallel running, between a spun-up run and a newly started run

The 4DVAR initial penalty ("J") has proven to be a useful diagnostic in monitoring the runs. Figure 12 shows initial J for each run of 4DVAR within stream A. The drop in J for a week early in the period reveals a problem. It was found that we had inadvertently removed

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surface observations from the assimilation.

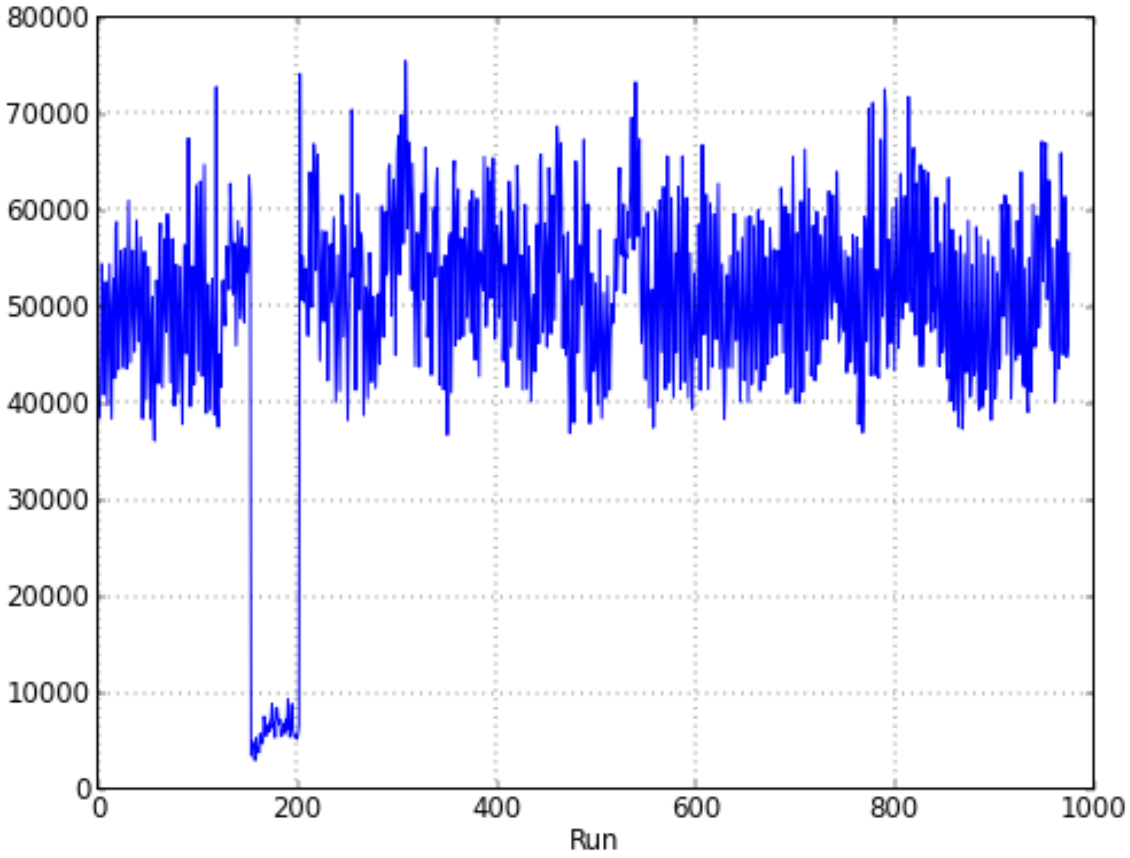

Figure 12 Initial 4DVAR penalty J for first reanalysis, stream A

4.2 Production Run

This is the definitive run that will be used in EURO4M validation activities.

Satellite radiances are used, with bias corrections calculated from data from the first reanalysis run. Upper air reports are taken from the MARS archive, and surface cloud is assimilated.

Again this was run as four parallel streams, and used initial conditions from the first reanalysis run, allowing a shorter spin-up than from ERA-Interim:

A: 15/11/2007 – 30/06/2008

B: 15/06/2008 – 31/12/2008

C: 15/12/2008 – 30/06/2009

D: 15/06/2009 – 31/12/2009

Figure 13 shows initial J for each run of 4DVAR over the entire period, and also final Jc. Jc is the constraint on high frequency increments (Section 1.2). There is a period April to June 2008 with very low Jc. This has been traced to an error where the perturbation

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forecast model within 4DVAR had been switched off so that the assimilation system was effectively 3DVAR. The period will be rerun using 4DVAR
correctly.

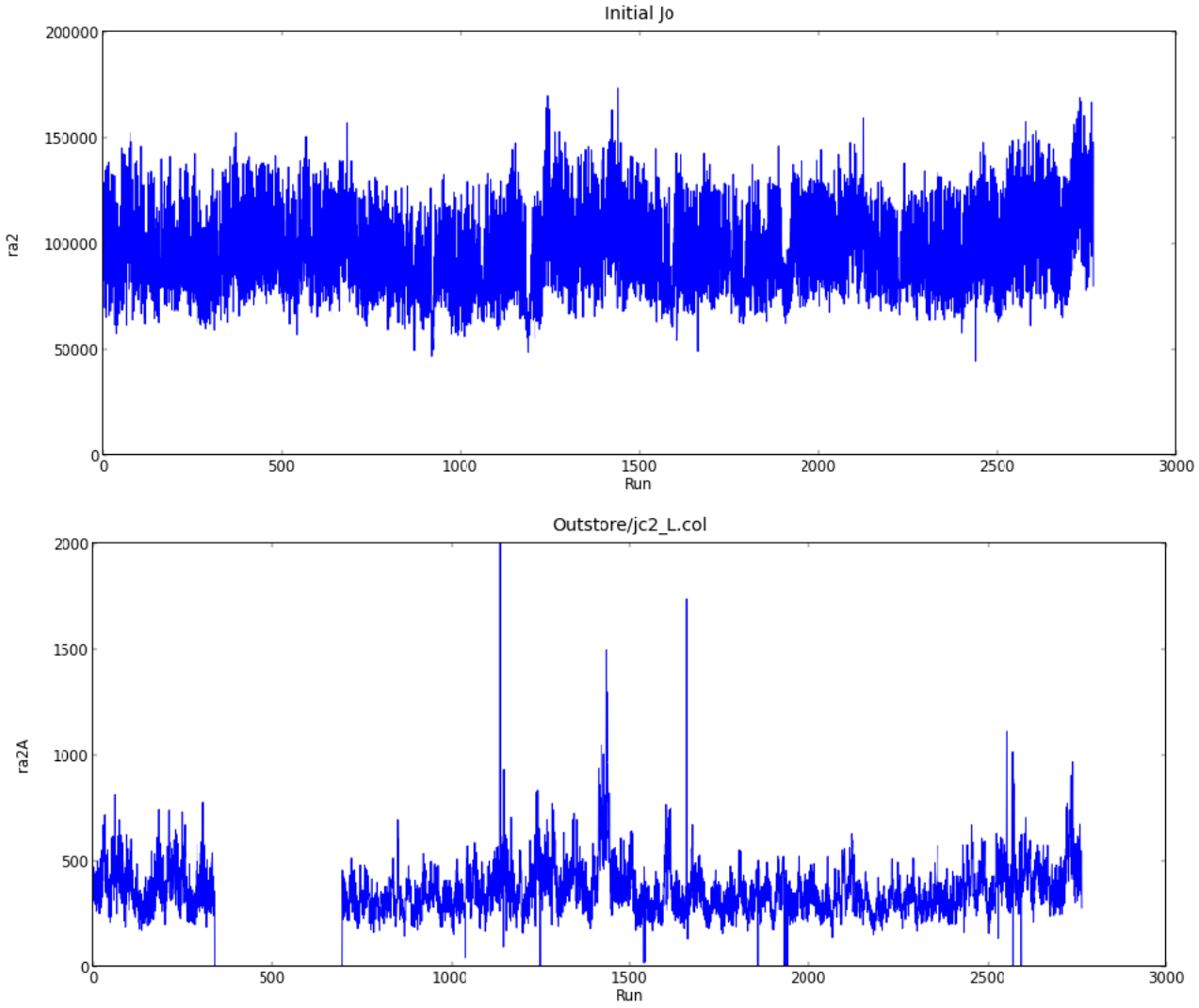

Figure 13 Initial penalty J (top) and final Jc (bottom) from 4DVAR, reanalysis production run

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5. Validation

5.1 Essential Climate Variables

A reanalysis system is of little value without knowledge of its accuracy and reliability. Tools have been developed to evaluate statistics and indices for a range of Essential Climate Variables (ECVs) from the reanalyses. These include 'extreme statistics' (defined as ‘core indices’ of climate change by the joint CCI/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices). These can be compared with observations statistics from ECA&D (European Climate Assessment & Dataset) (Haylock et al, 2008).

Figure 14 shows an example of maximum rainfall accumulation over any 5-day period in July 2008, from ERA-Interim (top) and Met Office initial reanalysis (bottom), with observations over-plotted. The area covers Romania, Moldova and Ukraine, which suffered from extreme flooding that month. The higher resolution of the Met Office reanalysis has allowed it to better model the extremes, which correspond to areas that were severely affected. In this case, neither the Met Office nor ERA-Interim reanalysis has captured the high values shown by observations further East.

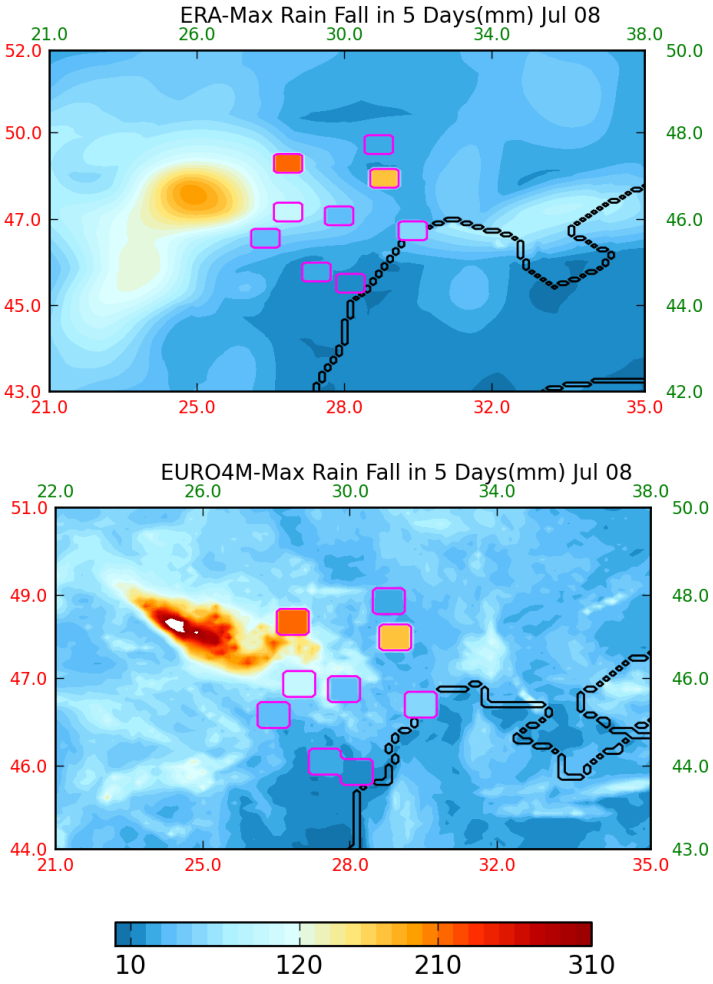

Figure 14: July 2008 max 5-day rainfall, ERA-Interim (top), Met Office reanalysis (bottom)

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5.2 List of climate indices

Monthly Core Climate indices:

- number of frost days
- number of summer days
- number of icing days
- number of tropical nights
- maximum of maximum screen level temperature
- maximum of minimum screen level temperature
- minimum of maximum screen level temperature
- minimum of minimum screen level temperature
- maximum 1-day precipitation
- maximum 5-day precipitation
- number of days with precipitation greater than 10mm
- number of days with precipitation greater than 20mm
- maximum length of dry spell
- maximum length of wet spell

Other Climate Indices:

- number of wet days
- number of mostly sunny days
- number of mostly cloudy days
- number of windy days
- number of calm days
- maximum of daily maximum wind gust

5.3 Validation methods, consistency and uncertainty

The reanalysis produces analyses and forecasts to T+24 four times a day. The quality of these fields is assessed by the Met Office verification software (VER). Since accurate short forecasts require accurate analyses, measuring the accuracy of the forecasts gives a measure of the quality of the reanalysis. VER provides statistics for a wide range of variables, comparing forecasts against observations. Comparison between reanalyses can be simplified by calculating a single number, the NWP index, that is a weighted sum of skill scores and equitable threat scores (ETS) for a selection of variables.

Monthly means and climate indices produced from reanalysis can be validated by comparison with the ECA&D dataset which includes the same measures calculated for observation stations.

The monthly means and climate indices are obtained by calculating means, maxima, minima etc. of variable from reanalysis data providing fields of means and climate indices. These can also be interpolated to produce location-specific time-series etc.

The indices make use of the following definitions:

Frost day daily minimum temperature is less than 0^{o}C
Summer day daily maximum temperature is greater than 25^{o}C
Icing day daily maximum temperature is less than 0^{o}C
Tropical night daily minimum temperature is greater than 20^{o}C

Wet day daily precipitation is greater than or equal to 1mm

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Dry day daily precipitation is less than 1mm
Wet spell period of consecutive wet days
Dry spell period of consecutive dry days

Mostly sunny days daily mean cloud is less than or equal to 2 oktas
Mostly cloudy days daily mean cloud is greater than or equal to 6 oktas

Windy days daily mean wind speed is greater than or equal to 6Bft or 10.8ms^{-1}
Calm days daily mean wind speed is less than or equal to 2ms^{-1}

Skill Score This is a measure of the improvement of a forecast compared to persistence.

$$skill = \frac{P^2 - F^2}{P^2}$$

where P and F are the RMS errors of persistence and forecast, respectively.

ETS Equitable Threat Score. This is a measure of the ability of a forecast to capture an event (e.g. >1mm precipitation).

$$ETS = \frac{A - S}{(B + C)T + A - S}$$

where A are the number of events forecast and registered in observations, B are the number of events forecast, but not registered in observations, C are the number of events registered in the observations, but not forecast, D are the number of events not registered in the observations and not forecast and T are the total number of events (T = A+B+C+D)

6. Early results

A full set of results will appear in later reports (EURO4M deliverables D2.8 and D2.9).

6.1 Skill scores

Verification and validation scores can be compared against those of the ERA-Interim global reanalysis. Figure 15 compares skill scores and ETS from the Met Office reanalysis against ERA-Interim, for T+6, over the whole 2008-9 period. For most variables, the higher-resolution reanalysis scores better. Pressure at mean sea level (PMSL) is an exception. Regional models often struggle to match global models in PMSL accuracy. The advantage of high resolution is countered by the difficulty of modelling large-scale flow in a limited area domain constrained by boundaries.

Figure 16 shows the Met Office's NWP index, a weighted average of the variables from Figure 15, over the period of the reanalysis. By this measure, the Met Office reanalysis generally scores better than ERA-Interim. Screen-level temperature shows a similar pattern (Figure 17). Scores for April to June 2008 are still positive despite the use of 3DVAR for this period (Section 4.2).

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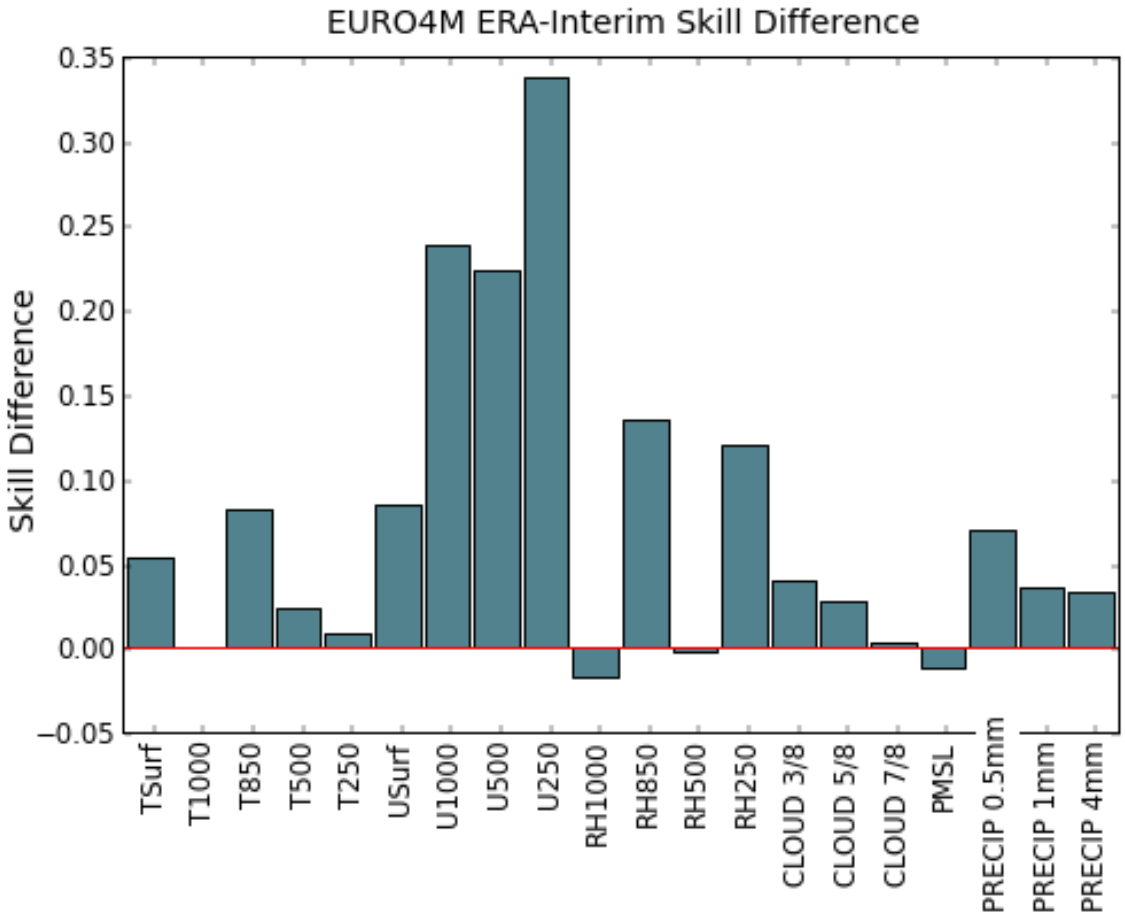

Figure 15: Skill score and ETS differences for EURO4M vs ERA-Interim, 2008-9

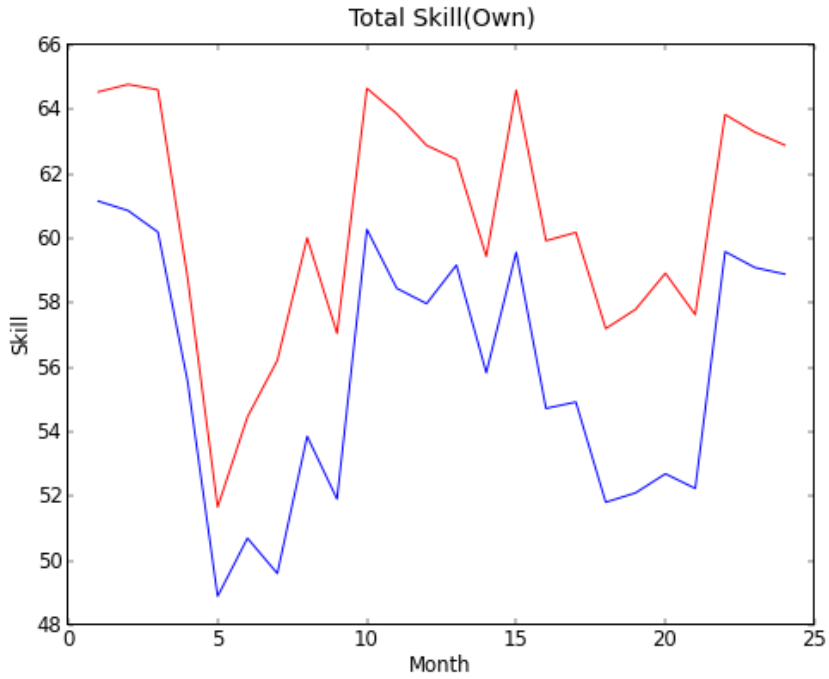

Figure 16: NWP index for 2008/9, ERA-Interim (blue) and EURO4M (red)

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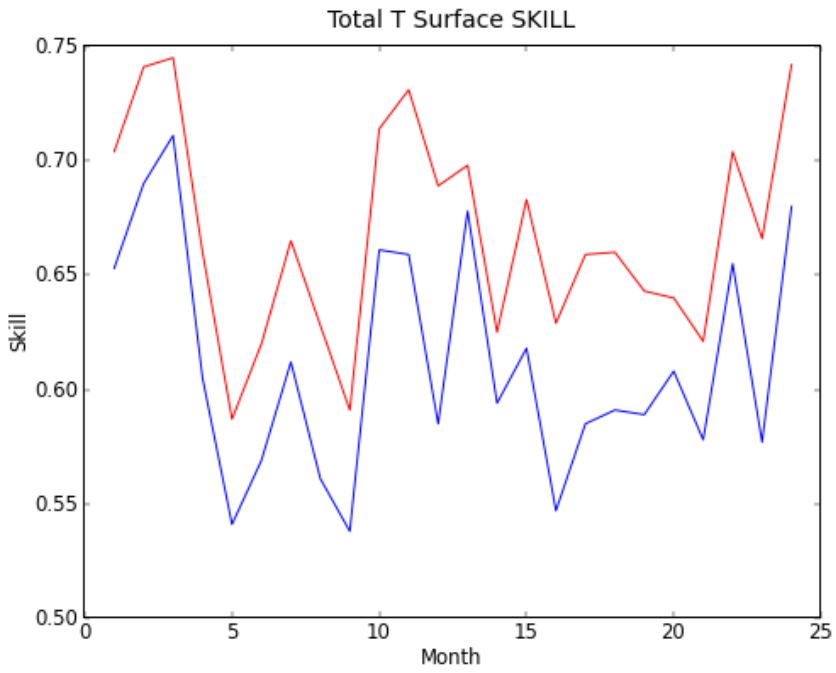

Figure 17: Screen-level T skill for 2008/9, ERA-Interim (blue) and EURO4M (red)

Figure 18 shows correlations between the Met office and ERA-Interim reanalyses and the ECA&D observation-derived mean temperatures for January and July 2008. For each available observation station the mean temperature is plotted against its reanalysis equivalent. The reanalysis value is obtained via bi-linear interpolation to the station position. For each reanalysis a line of best fit is calculated as well as the correlation coefficient (marked as R[XY] in Figure 18). For both months the observation-derived data has a greater correlation with the Met Office reanalysis than with ERA-Interim.

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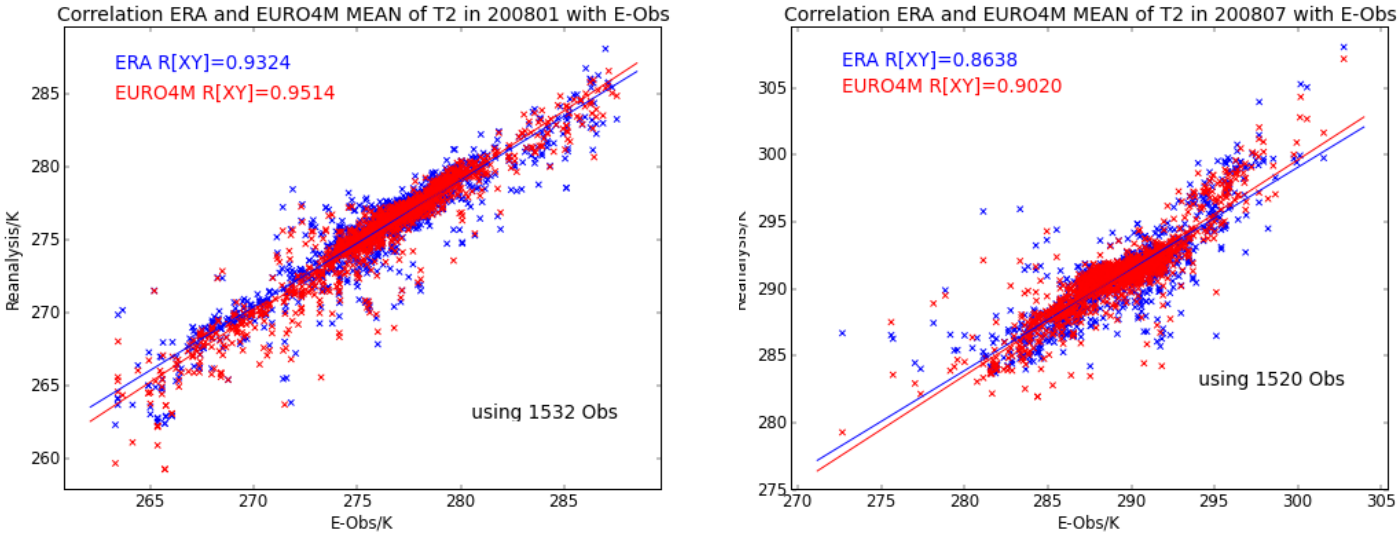

Figure 18: January and July 2008 Correlations between reanalyses and ECA&D observation-derived mean temperatures displaying results for ERA-Interim (blue) and Met Office (red) reanalysis.

6.2 Climate indices

Figures 19 and 20 show maximum values of daytime maximum screen-level temperatures from ERA-Interim and the Met Office reanalysis, for the month of July 2008. The two reanalyses show a similar range of values. The higher resolution of the Met Office reanalysis is clear.

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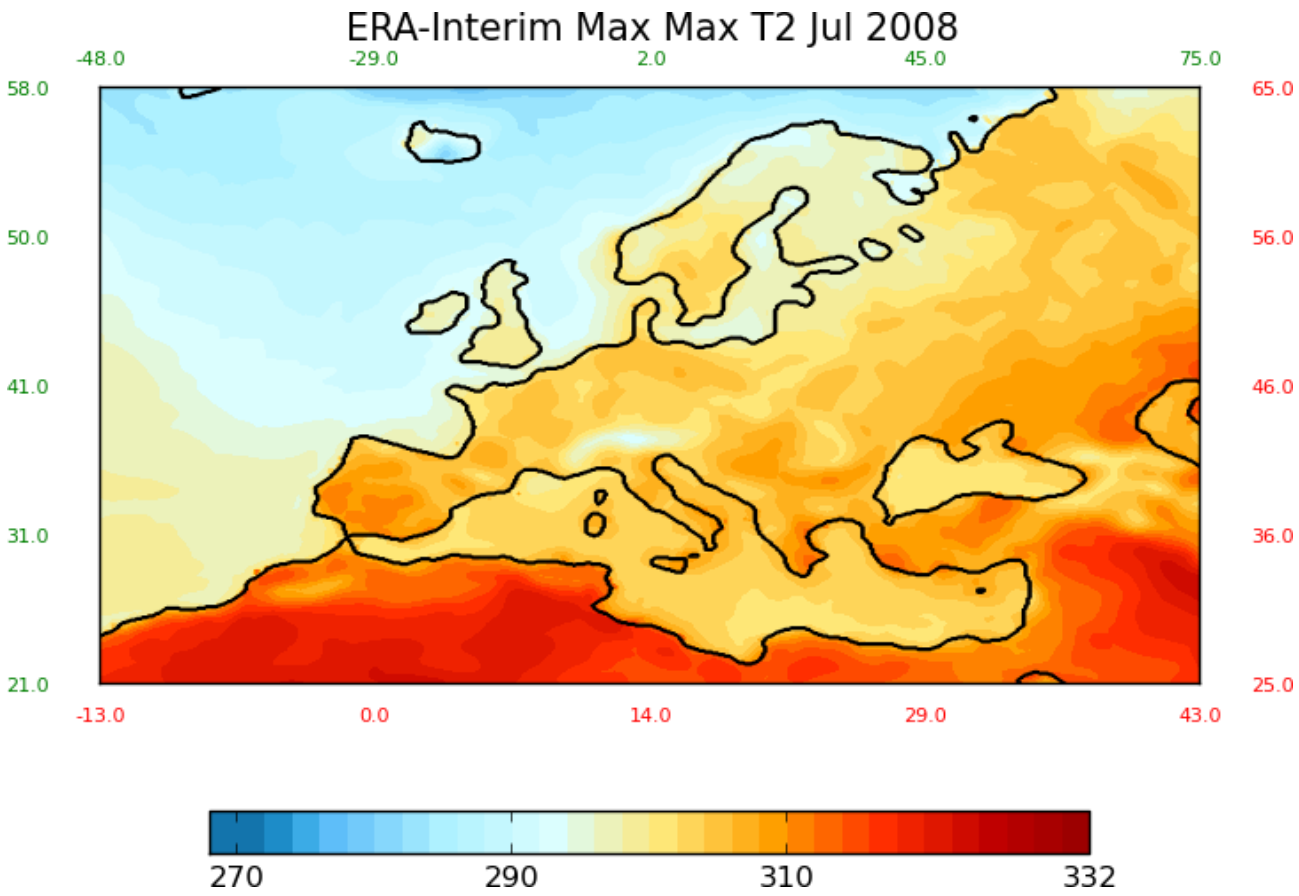

Figure 19: Max of daytime max temperature from ERA-Interim, July 2008

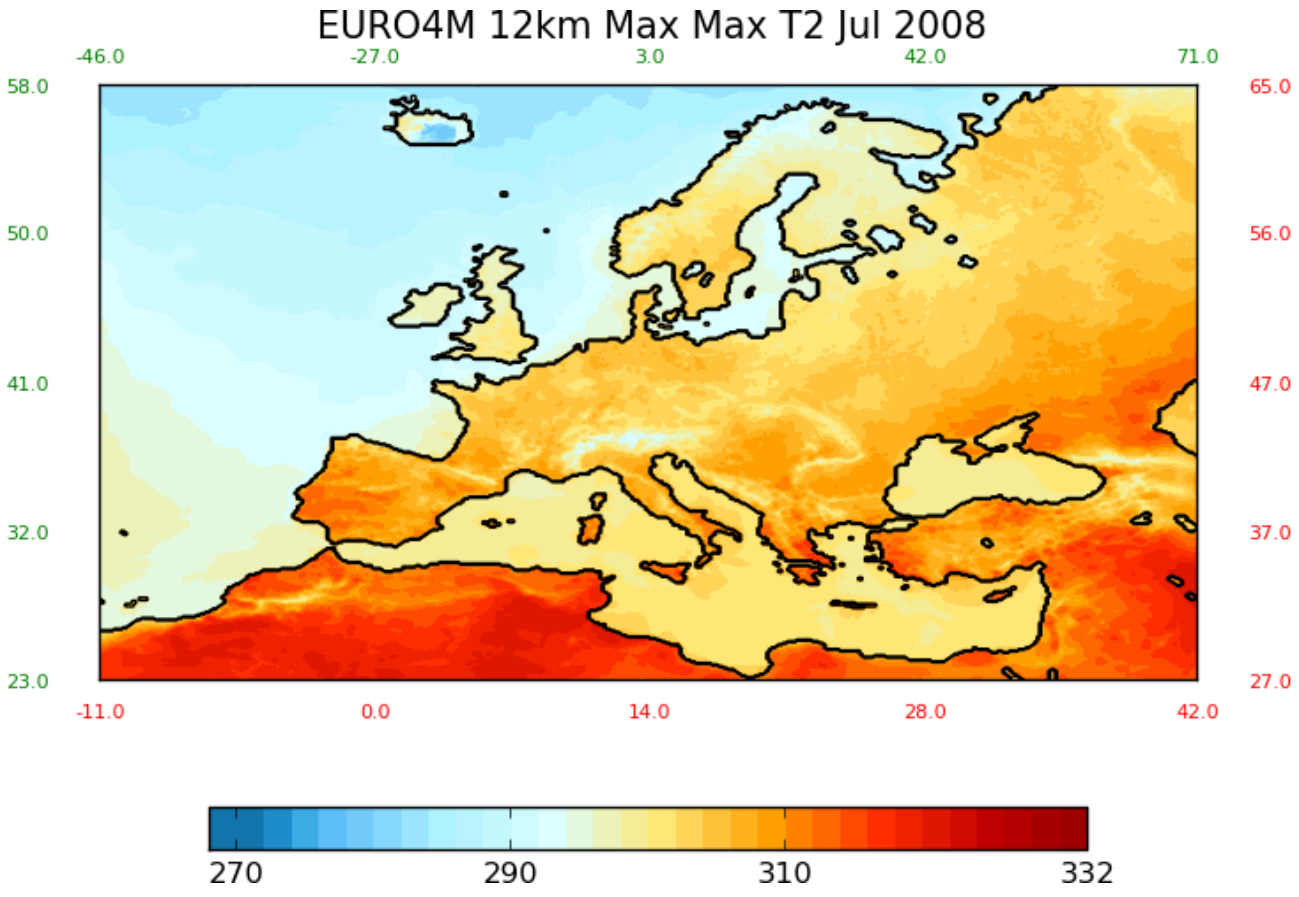

Figure 20: Max of daytime max temperature from Met Office reanalysis, July 2008

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7. Future work

7.1 Climate and Downscaler runs

Two runs have started with no data assimilation:

a. Climate style run, starting from ERA-Interim initial conditions, and then free running.

b. Downscaler run, starting from ERA-Interim every cycle, to produce a 24hr forecast.

Both runs use the same LBCs from ERA-Interim and the same 12km model domain as the reanalysis. These runs will provide a 3-way comparison with the reanalysis.

Jones & Macpherson (2012) have similarly compared the operational NAE against runs from the downscaled operational Global model. They found that the NAE gave significantly better screen temperature and visibility verification over the UK during the first 24 hours of the forecast, but that the downscaled run generally performed better for other variables. Data assimilation appeared to give a small benefit overall, while most of the benefit of the NAE over the Global could be explained by the increased horizontal resolution.

The global model was at 25km resolution while ERA-Interim is at approximately 80km resolution. That difference may mean that Jones & Macpherson's results might not apply here.

7.2 Precipitation assimilation

Work is underway to assimilate raingauge accumulations in 4DVAR. This was not ready for the production run and so the reanalyses available for evaluation will not include precipitation observations. This is planned to be ready later in the year, to be included in a final reanalysis run which will be evaluated before the end of the project.

7.3 Observational DataBase (ODB)

ODB is a portable, parallel, relational database system developed by ECMWF to store observations and model equivalent values (http://www.ecmwf.int/services/odb/). ECMWF have developed a range of tools to produce diagnostics from ODB, as used for instance for ERA-Interim in Dee et al (2011). The Met Office now has the capability of producing ODBs from its own systems. These will be produced from the production reanalysis, to give additional information on reanalysis performance.

7.4 Variational bias correction

Satellite biases change with time. The current Met Office offline system of generating

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satellite bias corrections is not ideal for reanalysis. Either a period must be run twice, the first time just to generate bias statistics, or corrections must be used from earlier in the run. Variational bias correction solves the problem by allowing the bias corrections to adapt in time. This has been demonstrated to work well in a global reanalysis (ERA-Interim: Dee & Uppala, 2009) but it is not clear whether it can work in a regional domain. Code is now in place at the Met Office to use variational bias correction. It is intended to test this in the regional reanalysis.

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